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Citation style:. Kozela A, Ban G., Białek A.,. Bodek K, Gorel P., Kirch K., Stephan Elżbieta i in. (2011). Free neutron decay and time reversal violation. "Acta Physica Polonica B" (Vol. 42, no. 3/4 (2011), s. 789-793), doi 10.5506/APhysPolB.42.789

FREE NEUTRON DECAY AND TIME REVERSAL VIOLATION*

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(Received January 28, 2011)

Both components of the transverse electron polarization have been measured in free neutron decay. The T-odd, P-odd correlation coefficient associated with polarization component perpendicular to the neutron polarization and electron momentum, was found to be $R = 0.006 \pm 0.012 \pm 0.005$. This value is consistent with time reversal invariance, and significantly improves limits on the relative strength of imaginary scalar couplings in the weak interaction. The value obtained for the T-even, P-even correlation coefficient connected with the second transversal polarization component, $N = 0.065 \pm 0.012 \pm 0.004$, agrees with the Standard Model expectation providing an important sensitivity test of the experimental setup.

DOI:10.5506/APhysPolB.42.789
PACS numbers: 24.80.+y, 23.40.Bw, 24.70.+s, 11.30.Er

1. Introduction

Increasing number of observables which became accessible in novel experimental techniques and at new generations of neutron sources allows not only to contribute in the determination of Standard Model (SM) parameters, but also to open the possibility to address some basic problems reaching beyond the SM.

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", August 30–September 5, 2010, Zakopane, Poland.

One of these is the physics of CP violation which, via CPT theorem, is equivalent to time reversal violation (TRV). The SM with the Cabbibo–Kobayashi–Maskawa mixing scheme [1] accounts for CP violation discovered in kaon [2] and B-meson [3, 4] systems. It fails, however, by many orders of magnitude, to account for the most striking evidence of CP violation: the dominance of baryonic matter over antimatter in the present Universe.

Many experiments have been performed and are underway with the motivation to search for new sources of CP violation. Experiments from high energy domain face one fundamental problem. Sizable contribution of heavy quarks can interfere in the dynamics of the observed process and makes the distinction between new physics and SM induced effects difficult.

Nuclear beta decay experiments are practically free from this obstacle and the decay of free neutron plays a particular role here: due to its simplicity it is free from model dependent corrections associated with the nuclear and atomic structure. Moreover, final-state interaction induced effects, which can mimic T violation, are small in this case and can be calculated with relative precision better than 1% [5]. There is no doubts that the discovery of new CP- or T-violating phenomena in such a system would be an important milestone.

Searches for the time reversal violation with free neutron as a laboratory concentrate around two different kinds of observables. The most precise are measurements of the electric dipole moment which is sensitive to CP-violating θ-term in QCD Lagrangian. Despite their impressive accuracy one obtains only upper bounds ($2.9 \times 10^{-26} e \times$ cm, [6]) which are still far from the SM predictions ($\approx 10^{-31} e \times$ cm) leaving room for new physics searches.

More than 50 years ago it has been recognized, that TRV may be tested also in various correlations accessible in nuclear or particles' decays [7]. In neutron β-decay, up to recently only one of them was investigated. It was the D coefficient, sensitive to imaginary part of vector and axial vector couplings of the weak interaction, describing the angular correlation between the electron and antineutrino momenta and the neutron spin [9, 10].

In this report we present preliminary results of an extended and improved analysis of the first measurement of the R correlation coefficient in neutron decay. Improvement in the accuracy of the determination of R coefficient compared to our previous result [12] is a consequence of two major extensions in the analysis of existing data: *(i)* the analysis of additional event class with backscattered electron trajectories contained within the vertical plane, and *(ii)* improved determination of the effective analysing powers of the applied Mott targets. Minor changes in the value of N-correlation coefficient are solely the result of new effective analysing powers.

2. Experiment

The experiment was performed at the FUNSPIN beam line at the neutron source SINQ of the Paul Scherrer Institute, Villigen, Switzerland. The applied apparatus consisted of two identical modules, arranged symmetrically on both sides of the cold neutron beam (Fig. 1). The whole structure was mounted inside a large volume dipole magnet providing a homogeneous vertical spin-holding field of 0.5 mT. The orientation of the neutron beam polarization was reversed at regular time intervals. Going outwards from the beam, each module consists of a multi-wire proportional chamber (MWPC) for electron tracking, a removable Mott scatterer (1–2 μm Pb layer evaporated on a 2.5 μm thick Mylar foil) and a scintillator hodoscope for electron energy measurement. See [11] for more details.

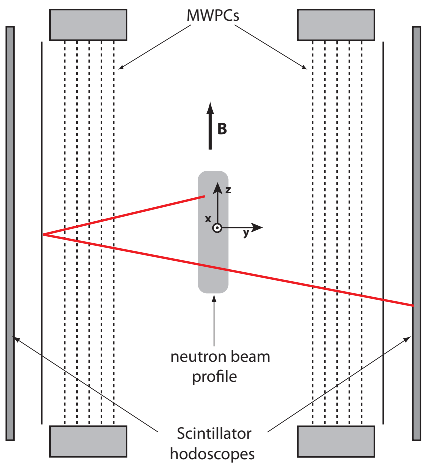

Fig. 1. Schematic front view of the experimental setup. A sample projection of an electron V-track event, bearing information on R correlation, is indicated.

3. Analysis

Following [7] the N and R coefficients can be defined using the decay rate distribution of electrons from a sample of polarized neutrons

$$W(\boldsymbol{J}, \hat{\boldsymbol{\sigma}}, E, \boldsymbol{p}) \propto 1 + \frac{\boldsymbol{J}}{J} \times \left(A\frac{\boldsymbol{p}}{E} + R\frac{\boldsymbol{p} \times \hat{\boldsymbol{\sigma}}}{E} + N\hat{\boldsymbol{\sigma}} \right) , \tag{1}$$

where E and $\boldsymbol{p}$ are electron energy and momentum, $\boldsymbol{J}$ is the neutron spin, $\hat{\boldsymbol{\sigma}}$ is a unit vector onto which the electron spin is projected and A is the decay asymmetry parameter. With the usual SM assumptions ($C_{\rm V} = C'_{\rm V} = 1$, $C_{\rm A} = C'_{\rm A} = -1.27$ [8]), and allowing for a small admixture of scalar and tensor couplings $C_{\rm S}$, $C_{\rm T}$, $C'_{\rm S}$, $C'_{\rm T}$, N and R coefficients can be expressed as

$$N = -0.218 \times \Re\left(\frac{C_{\rm S}+C'_{\rm S}}{C_{\rm V}}\right) + 0.335 \times \Re\left(\frac{C_{\rm T}+C'_{\rm T}}{C_{\rm A}}\right) - \frac{m}{E} \times A\,, \quad (2)$$

$$R = -0.218 \times \Im\left(\frac{C_{\rm S}+C'_{\rm S}}{C_{\rm V}}\right) + 0.335 \times \Im\left(\frac{C_{\rm T}+C'_{\rm T}}{C_{\rm A}}\right) - \frac{m}{137\,p} \times A\,, \quad (3)$$

where m is the electron mass. The R correlation value vanishes to the lowest order within the SM. Including final-state interactions (last term in Eqs. (2), (3)) it becomes different from zero, $R_{\rm FSI} \approx 0.0006$, however, still below the sensitivity of the present experiment. A larger measured value would provide a hint for the existence of exotic couplings, and a new source of TRV.

To extract the N and R correlation coefficients the following asymmetry has been considered

$$\mathcal{A}(\alpha) = \frac{n^+(\alpha) - n^-(\alpha)}{n^+(\alpha) + n^-(\alpha)} = P\bar{\beta}A\bar{F}(\alpha) + P\bar{S}(\alpha)\left[N\bar{G}(\alpha) + R\bar{\beta}\bar{H}(\alpha)\right]\,, \quad (4)$$

where $n^{\pm}$ represent background-corrected experimental numbers of counts of V-track events, sorted in 12 bins of α, defined as the angle between electron scattering and neutron decay planes. $\bar{S}$ is the effective analysing power of the electron Mott scattering, $\bar{\beta}$ is the average electron velocity, P corresponds to the average beam polarization, and $\bar{F}$, $\bar{G}$, $\bar{H}$ are kinematic factors [12].

The obtained value of R coefficient, $0.006 \pm 0.012 \pm 0.05$, is consistent with time reversal invariance, and significantly improves the limits on the relative strength of imaginary scalar couplings in the weak interaction (see Fig. 2).

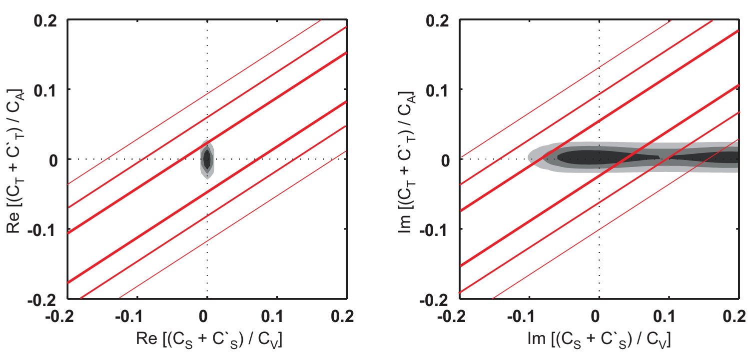

Fig. 2. Experimental bounds on the scalar *vs.* tensor normalized couplings. Lines represent the result of this work 1, 2 and 3 σ respectively, while the grey areas illustrate corresponding limitations from former existing experiments as collected in [13].

The value of $N = 0.065 \pm 0.012 \pm 0.004$, agrees with the Standard Model expectation, providing an important sensitivity test of the experimental setup. The total uncertainty of this measurement is dominated by the statistical error. The main contributions to the systematic error are generated by the background subtraction procedure, the influence of $P\bar{\beta}A\bar{F}$ term (Eq. (4)) and the uncertainty of the determination of effective analysing power $\bar{S}$. This is the first experimental determination of the R correlation coefficient in neutron decay and first observation of a finite value of the coefficient N in nuclear decay.

A new method for the derivation of the R correlation coefficient is under development. It is based on the analysis of the ratio

$$U = \frac{\sqrt{n^-(\alpha)\, n^-(-\alpha)} - \sqrt{n^+(\alpha)\, n^+(-\alpha)}}{\sqrt{n^-(\alpha)\, n^-(-\alpha)} + \sqrt{n^+(\alpha)\, n^+(-\alpha)}} \approx P\bar{\beta}A\bar{F} + R\,P\bar{S}\bar{H} + \eta/2 \quad (5)$$

which, in the lowest order, is insensitive to N coefficient. This allows to avoid two parameter fit and correlation with the N coefficient, which was the case in the previous analysis. From the construction of U it follows that it is also sensitive to the V-track reconstruction efficiency, η, correlated with the sign of neutron beam polarization. This, however, was very well controlled in our apparatus and the associated systematic error is negligible. The results are promising, but new systematic effects induced by magnetic guiding field need farther investigations.

REFERENCES

[1] M. Kobayashi, T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).

[2] J.H. Christenson *et al.*, *Phys. Rev. Lett.* **13**, 138 (1964).

[3] K. Abe *et al.*, *Phys. Rev.* **D66**, 071102 (2002).

[4] B. Aubert *et al.*, *Phys. Rev. Lett.* **89**, 011802 (2002).

[5] P. Vogel, B. Werner, *Nucl. Phys.* **A404**, 354 (1983).

[6] C.A. Baker *et al.*, *Phys. Rev. Lett.* **97**, 131801 (2006).

[7] J.D. Jackson, S.B. Treiman, H.W. Wyld, *Nucl. Phys.* **4**, 206 (1957).

[8] C. Amsler *et al.* [Particle Data Group], *Phys. Lett.* **B667**, 1 (2008).

[9] L.J. Lising *et al.*, *Phys. Rev.* **C62**, 055501 (2001).

[10] T. Soldner *et al.*, *Phys. Lett.* **B581**, 49 (2004).

[11] G. Ban *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A565**, 711 (2006).

[12] A. Kozela *et al.*, *Phys. Rev. Lett.* **102**, 172301 (2009).

[13] N. Severijns, M. Beck, O. Naviliat-Cuncic, *Rev. Mod. Phys.* **A78**, 991 (2006).